A Conceptual Model to Adjust Fugitive Dust Emissions to Account for Near Source Particle Removal in Grid Model Applications

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Background and Introduction

For a number of years air quality analysts have recognized that fugitive dust emission inventories, when coupled with air quality models, substantially overestimate PM2.5 ambient crustal material when compared to the crustal material found in ambient samples. In the mid 1990's, the U.S. Environmental Protection Agency's (EPA) Office of Air Quality Planning and Standards (OAQPS) began to use, as an interim measure, a factor to "adjust" the fugitive dust emission estimates in regional modeling analyses to obtain better agreement between the regional model results and ambient data. This adjustment was an ad hoc "one value fits all" approach to reduce the disparity between modeling and ambient data but it did not address possible regional differences in the adjustment factor. The adjustment factor was conceived with the acknowledgement that an investigation was needed to identify what specific problems in the inventory and model were causing the discrepancy. Since the late '90s, the EPA has been actively working to understand the nature of those specific problems. Emphasis has been on developing a conceptual model of the potential dust removal processes near the source and on field work to evaluate the removal effectiveness. Much work has been accomplished and refinements to the "divide-by-four" national factor are proposed, even as work continues to refine both the inventory methodology and models.

Fugitive dust categories of interest include unpaved and paved road dust, dust from highway, commercial and residential construction, agricultural tilling, windblown dust from agricultural and other exposed land, quarrying and other earthmoving. Of these, unpaved roads are the highest single emissions category, accounting for about one third of non windblown fugitive dust emissions. Windblown dust and tilling are also large emissions categories. This paper discusses some recent studies and proposes refinements to the "divide-by-four" factor that may be applicable to these source categories.

DRI / EPA Workshop

Several years ago the Desert Research Institute (DRI) and EPA/OAQPS convened a workshop to begin the process of understanding why modeled and monitored crustal material fractions do not agree. As follow-up to this workshop, OAQPS documented that the measurements underlying the dust emission estimates were made generally within 5-10 meters of the source and that 75% of the dust plume is less than 2 meters above ground level at the location where the measurements are made. Based on this information and other workshop discussions, DRI concluded that, since the dust plume is still turbulent and very close to the ground, substantial dust removal processes can occur near the source, including impaction on vegetation and structures and enhanced deposition through a variety of mechanisms. They concluded that air quality models (as they are currently applied) do not adequately account for injection height, deposition losses and impaction losses near fugitive dust emission sources. They further noted that since 75% of the dust plume from such sources is less than 2 meters above ground level at the location where the emission

measurements are made, it is a reasonable "first approximation" that this portion of the emissions are removed within several hundred meters of the source. They noted that in practice, this removal fraction would vary and that additional testing is needed.
[Watson, John G., Judy Chow and contributors (2000). Reconciling Urban Fugitive Dust Emissions Inventory and Ambient Source Contribution Estimates. Desert Research Institute Report 6110.4F Prepared for U.S. EPA, Research Triangle Park, NC. May 2000]
http://www.epa.gov/ttn/chief/efdocs/fugitivedust.pdf .

WRAP Expert Panel on Fugitive Dust
The DRI / EPA Workshop was followed by the formation of an Expert Panel on Fugitive Dust, sponsored by the Western Regional Air Partnership (WRAP) and chaired by Dr. Richard Countess. The panel concluded that not all suspendable particles are transported long distances. Specifically, the report supported the conclusion of the DRI Workshop that much of the ground level fugitive dust emissions from soil disturbed by man's activities are likely to be removed close to the source. The low release height and turbulence leaves the particles temporarily close to the ground where they are subject to removal by impaction on nearby horizontal and vertical surfaces, including vegetation and structures. The Countess report recommends field studies to expand upon the current knowledge of the removal effectiveness of trees, desert shrub and buildings.
[Countess, Richard, W. Barnard, C. Claiborn, D. Gillette, D. Latimer, T. Pace, J Watson, "Methodology for Estimating Fugitive Windblown and Mechanically Resuspended Road Dust Emissions Applicable for Regional Air Quality Modeling", EPA Emissions Inventory Conference, Denver CO 2001]
http://www.epa.gov/ttn/chief/conference/ei10/fugdust/countess.pdf
http://www.wrapair.org/forums/dejf/documents/FugativeDustFinal.doc

The Role of Surface Cover (Vegetation & Structures) in Removal of Airborne Dust
Early research into the general area of dust removal was done by Slinn for the U. S. Dept. of Energy. Much of Slinn's work focused on particle removal from air flowing above a tree canopy, but he also discussed the concept of a "stilling zone" within and below the canopy. Within the stilling zone, wind velocity is so much reduced that particles have ample time to settle to the ground or impact on the canopy or groundcover.
[Slinn, W.G.N (1982). "Predictions for Particle Depositions to Vegetative Canopies", Atmospheric Environment, 16: 1785-1794].

Windbreaks have long been a staple of soil erosion prevention, although most of the research has focused on the use of windbreaks placed upwind of a field to reduce the wind speed (and thus erosion) over the field. More recent work has focused on the effectiveness of vegetation as a removal mechanism. Anecdotally, researchers feel that the forest is a very good filter, both horizontally and vertically. Moreover, field tests suggest that the transmittance of dust through a windbreak is close to the optical transmittance. In other words, if the foliage is dense enough to block light, it also effectively filters particles.
[Ron Cionco, Army Research Lab, Personal Communication to T. G. Pace, June 25, 2002]
[Raupach, M.R., Woods, N., Dorr, G., Leys, J.F. and Cleugh, H.A. (2001). The entrapment of particles by windbreaks. Atmospheric Environment 35, 3373-3383.]
[Raupach, M.R., and F.L. Leys (1999). "The efficacy of Vegetation in Limiting Spray Drift and Dust Movement Prepared for Dept of Land and Water Conservation, Gunnedah, Australia by CSIRO, Canberra, Australia"].

Thus, the combined work of Slinn, Cionco and Raupach, the DRI workshop and the WRAP Expert Panel on Fugitive Dust suggest that fugitive dust particles have ample opportunity to be removed near the source, through impaction or filtration onto vegetation or structures. The effect of surface cover is expected to be highly variable, depending on the nature and proximity of vegetation to dust sources. They note that surface cover that is taller, denser and closer to the source captures a larger amount of the particles, with the most capture occurring when a narrow source is surrounded on both sides by tall, dense vegetation such as a road within a forest. According to Cowherd and Pace, an exception to this is that particles transported toward (not generated within) non porous surfaces such as buildings or very dense vegetation may be diverted above or around those surfaces.

Cowherd and Pace suggest the use of a "limiting cases" conceptual model as a way to bound the dust capture potential of vegetation and structures. An unpaved road in the forest would represent one extreme or limiting case whereby most, if not essentially all of the road dust would be captured within the vegetation canopy. At the other extreme or limit, road emissions in the arid southwest would be subject to virtually no capture or removal due to vegetation. Other surface characteristics would fall between these limits.

Particles may be removed near the source by mechanisms other than impaction and filtration by surface cover. These processes include enhanced deposition near the source due to electrostatic forces, thermal deposition and particle agglomeration. These removal processes don't often affect particles in thermally buoyant or elevated plumes because the plumes rise above the ground obstructions and dilute more quickly. No field testing is available to directly quantify the effects of electrostatic and thermal processes or agglomeration on particle removal. However, Cowherd (2003) found particle removal rates near the source from a plume passing over an open field were higher than expected from capture by surface cover alone. He posed that thermal and electrostatic processes could partially explain those results.

[Cowherd and Pace (2002). Paper # 55552 "Potential Role of Vegetative Groundcover in the Removal of Airborne Particles", Proceedings of Air and Waste Management Association Annual Meeting, Baltimore MD, June 2002].
[Cowherd, Chatten and Dick L. Gebhart. Paper #69393 "Vegetative Capture of Dust From Unpaved Roads," Proceedings of Air and Waste Management Association Annual Meeting, San Diego, CA, June 2003].
[Flagan, R. C. 2001. Electrical Techniques In Aerosol Measurement, 2nd Edition (edited by P. A. Baron and K. Willeke). John Wiley and Sons, New York.]
[Gieseke, J. Q. Thermal Deposition of Aerosols. In Air Pollution Control, Part II (edited by W Strauss), Wiley-Interscience, New York. 1972]

Figure 1 illustrates the conceptual model for near source particle removal by vegetation, structures and other deposition enhancing factors.

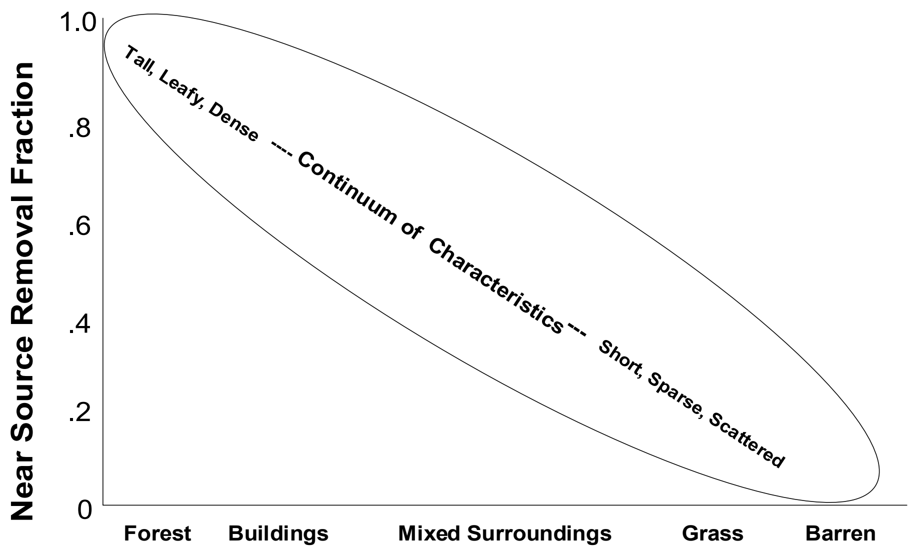

Figure 1. Conceptual Model – Potential for Near Source Particle Emissions Removal vs Type of Surroundings

Terminology

Cowherd and Pace (2002) refer to the fraction of a source's mass emissions captured by the vegetation (or other surface obstructions) as the "Capture Fraction (CF)" where
0 >= CF <= 1, where 0 is a barren landscape and 1.0 is within a dense forest. However, as discussed above, other "Enhanced Deposition (ED)" mechanisms may be active locally, i.e., electrostatic and thermal forces and agglomeration which creates larger particles that enhance gravitational settling. Together, the CF and other ED comprise the "Near Source Emissions Removal" (NSER).

(1) Near Source Emissions Removal (NSER) = (SE * CF) + (SE - SE * CF) * ED

(2) Transportable Emissions (TE) = Source Emissions (SE) - NSER, or

(3) TE = Source Emissions – (SE * CF) – (SE- SE * CF) * ED and

(4) Transportable Fraction (TF) = TE/SE

The term "Transportable Fraction" (TF) is adapted from the Watson & Chow (2000) and is used to describe those particles remaining available for transport out of the vicinity of the source, after local removal has occurred. Equation 3 is configured to reflect that other ED only affects those emissions that are not removed by Capture. Note that Equation. 3 constrains TE to be a positive quantity of emissions whose value is always less than or equal to the Source Emissions.

Recent and Ongoing Work to Evaluate Local Removal Mechanisms

Field work was recently completed for the Western States Air Resources (WESTAR) Council by a team of scientists including Dr. Vic Etyemezian at DRI. In this report, the effect of vegetation and structures on nearby unpaved road emissions was documented. The report supports the Countess findings, noting a wide range of downwind removal rates depending on surface conditions. The DRI results showed little removal in daytime tests in a sparse, barren environment, but a nighttime removal rate of 85 percent was found at a distance of 95 meters downwind when structures were present near the road.
[Etyemezian, V et al (2003a). Field Testing and Evaluation of Dust Deposition and Removal Mechanisms – Final Report. Desert Research Institute, Reno, NV, January, 2003.]
http://www.westar.org/Docs/Dust/Transportable_Dust_Final_Report_DRI_WESTAR.pdf

The field study recently conducted for the U.S. Department of Defense (DOD) measured the effect of groundcover on particle removal near an unpaved road (Cowherd and Gebhart, 2003). Initial tests were done over an open field 20 meters wide. In this test, the particles were depleted by 31 percent as they passed over the field. The dust depletion almost doubled, to over 57 percent when a bank of cedar trees was added downwind about 8 meters from the unpaved road. The amount of depletion was comparable for both PM2.5 and PM10 over these distances and test conditions.

The data from these tests is limited and more testing is needed to increase the statistical validity of the results. However, substantial near source removal of the particles is apparent, even during the daytime for particles passing over an open field. Cowherd suggests that other ED may have played a substantial role in particle depletion over the open field. Etyemezian (2003) saw no apparent effect of other ED over barren land. Thus, the influence of other ED is not clear from these tests, but its potential role in near source removal of particles cannot be ignored and research is needed. Tentatively, other ED is estimated to be: $0 > ED <= 0.2$. This range is well within the experimental error for both Etyemezian's and Cowherd's work.
[Cowherd, Chatten and Dick L. Gebhart. Paper #69393 "Vegetative Capture of Dust From Unpaved Roads," Proceedings of Air and Waste Management Association Annual Meeting, San Diego, CA, June 2003]

Figure 2 compares the results of the Cowherd and Etyemezian field tests with the NSER conceptual model shown in Figure 1. Test results from the two field studies were added to the schematic of the conceptual model based on descriptions of surface cover between the source and the test instruments. The NSER conceptual model shows reasonable agreement with these field tests and thus, it appears to provide a useful framework for making preliminary estimates of CF and other ED, based on local surface cover characteristics.

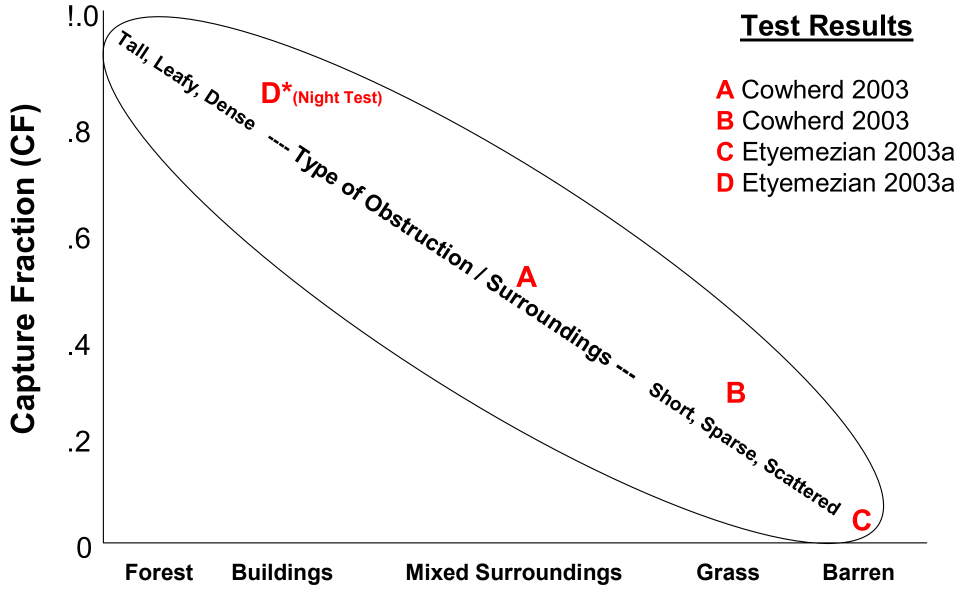

Figure 2. Comparison of Test data with CF Conceptual Model

Application of NSER Conceptual Model to Specific Locations

Use of Figure 1 to estimate values of CF for specific geographic areas requires use of a surface cover dataset such as the Biogenic Emission Land cover Database (BELD). BELD is a compendium of surface cover (mainly vegetation) characteristics used by the Biogenic Emission Inventory System (BEIS) biogenics emission model (Birth & Geron 1995). It contains data on several hundred species of vegetation at a 1 km cell size. For this analysis, county-level summaries were used; note however, regional air quality models such as the Community Multiscale Air Quality Modeling System (CMAS) can in principle, access the 1 km dataset to give enhanced spatial resolution.

The BELD dataset also includes estimates of height and leaf characteristics for key species in its database. Typically, grasses are assumed to be 0.5 m high , trees (11-38 m) and crops (0.5 – 1.5 m). The leaf area index (LAI, an indication of leaf density) is also given, but the example calculations herein only consider differences in particle removal effectiveness due to the LAI in a very general way. Evaluation of research on the effectiveness of specific vegetative and structural types on dust removal may enable refinement of the CF's in the future.

[Birth, T.L. and C.D. Geron (1995). Users Guide to the Personal Computer Version of the Biogenic Emissions Inventory System (PC-BEIS) Version 2.0, Prepared by CRC for US EPA/AEERL, RTP, NC March 1995.]
http://www.cmascenter.org/

Information is not available to determine the microenvironment and amount of vegetation around each specific dust source. Thus, we must estimate the CF based on the range of vegetative characteristics in a larger land area. Such characteristics are available at the county level in the BELD data base. In this analysis, the surface covers described in BELD were qualitatively grouped into six cover types (barren & water; agricultural; grasses; scrub and sparsely wooded; urban; and forested). Then, Figure 1 was used to estimate the CF for each of the cover types:

Barren & Water ~ 0.03; Agricultural ~ 0.15; Grasses ~ 0.3; Scrub and sparsely wooded ~ 0.4; Urban ~ 0.7; and Forested ~ 0.95.

The fraction of land area assigned to each surface cover type was determined for each county from BELD. The county average transportable fraction was estimated by combining the CF's above with their fractional surface cover in each county and computing a weighted average CF for each county. Figure 3 shows the results of this calculation for each county in the U.S. Figure 3 was prepared using only the CF (ED was set = 0). As discussed previously, additional removal likely occurs near the source due to ED (thermal, electrostatic and agglomeration effects). If the effect of ED were included, along with the CF's the net effect would be to decrease the TF's presented in Figure 3.

Note that the effect of atmospheric stability on CF and other ED needs to be considered in the conceptual model. Both the CF and ED will likely be reduced under unstable atmospheric conditions which can cause the plume will rise above the earth's surface more quickly. Conversely, the removal due to capture and other ED could be enhanced even more under very stable conditions. Typically, the atmosphere will be more stable in the evening and less stable in the afternoon. In general, one would expect the role of atmospheric stability in near source particle removal to be less important when vegetation or structures are tall and/or are located near the dust source.
[Etyemezian, V. Personal Communication to T.G. Pace, June 2003b]

Figure 3 shows how the TF varies by county across the US, depending on the variation in surface cover. The differences are apparent across the heavily forested areas in the southeast and the Pacific NW, the arid areas of the Southwest, the agricultural breadbaskets of the Central US and the San Joaquin Valley in CA. Note that nationally, the county average CF ranges from 0.05 to 1.0. It averages approximately 0.56 across all counties in the WRAP State / Tribal domain and 0.47 in the 37 eastern states and Washington D.C. (0.35 in the northeastern and southeastern States and 0.6 in the midwest and central States). The county average CF's in Figure 3 represent the first attempt to apply the conceptual model to estimate how dust removal by ground level airflow obstructions might vary across the US; they will be revised as more information becomes available. Note that thus far, the transport fraction concept has only been applied on a county level, but it could easily be extended to a model grid level.
[Pace and Cowherd (2003). Paper # 70445 "Estimating PM-2.5 Transport Fraction Using Acreage-weighted County Land Cover Characteristics – Example of Concept", Proceedings of AWMA Annual Mtg, San Diego CA, June 2003.]

The TF's shown in Figure 3 were provided to the WRAP by OAQPS for use with their recently completed unpaved road dust emissions inventory. Note that the CF estimates for surface cover types in this paper have been revised slightly from the values which were provided to the WRAP - the urban CF used for the WRAP analysis was 0.6 (now 0.7) and the sparsely wooded & scrub CF was 0.7 (now 0.4). Also, note that the estimated CF's herein may be too high for windblown dust events because the wind's turbulence will usually lift particles higher more quickly and the opportunity for vegetative removal may be reduced. Also, as noted above, the TF's would be lower when ED is set > 0.0.

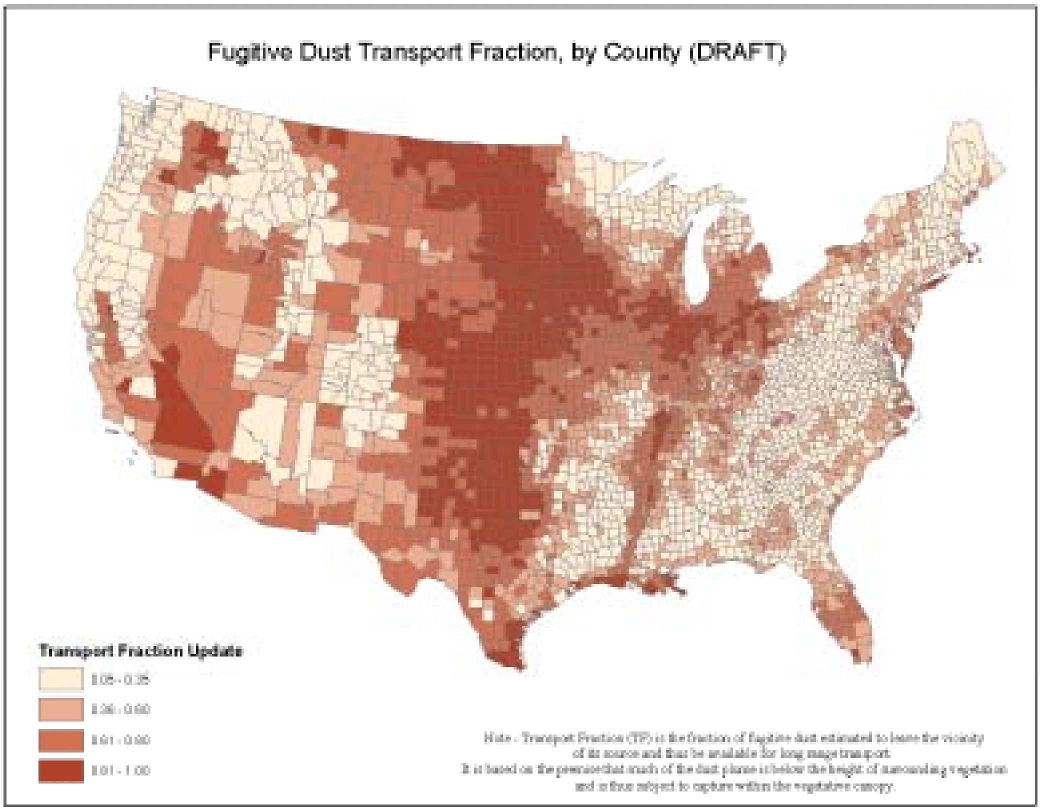

Figure 3. National Map Illustrating Concept of Fugitive Dust Transport Fraction

Countess recently applied the Transport Fraction (TF) concept to modeling in the San Joaquin Valley. He used the method posed by Pace and Cowherd to develop county specific TF's based on weighted average land use and ground cover information for the SJV counties. He found that use of those TF's resulted in adjusted emission estimates that agree well with ambient measurements in these SJV counties.
[Countess, R (2003). "Reconciling Fugitive Dust Inventories with Ambient Measurements", presented at the US EPA EI Conference, April 2003, San Diego, CA]
http://www.epa.gov/ttn/chief/conference/ei12/fugdust/countess.pdf

Related Work

The EPA is developing a module to estimate fugitive dust emissions and near source removal due to vegetation and urban structures. This module is intended to interface with the SMOKE emissions processing model and the CMAS modeling system. It will access meteorological parameters estimated by the MM5 model to provide a dynamic estimate of emissions for wind generated particles, emissions generated by man's activities and dust suppression by precipitation. The estimated completion date for this module is summer, 2004.

[He, Shan, Jason Ching, Dale Gillette, William Benjey, Thompson Pace, Thomas Pierce (2002). "Modeling Fugitive Dust in US with Models-3 Community Multi-scale Air Quality Modeling System", Presented at AAAR Annual Meeting, Charlotte, NC, October 2002]

Recently, several researchers and modeling practitioners have identified issues associated with how air quality models treat ground level emissions and how current models and modeling practices can lead to an underestimate of particle removal. Some of these issues were recently documented by staff at the Idaho Department of Environmental Quality (Idaho DEQ 2003). They concluded that Eulerian grid models generally over-predict coarse particle (2.5 ~ 10μm) concentrations by as much as a factor of 1.7 to 11, due primarily to the fact that these models artificially re-mix the particles in the lowest modeling layer at each time step [Dong, 2003]. DRI, in their work for DOD, also evaluated the removal mechanisms in the Atmospheric Diffusion Equation and in ISC3. They found the ISC better suited to analyze near field dispersion (Etyemezian 2003). Irwin noted that both grid and Gaussian models can deal with most of the removal mechanisms incorporated into CF and ED, but that many of the parameters are empirical and there is little guidance or supporting research on how to set the input parameters in these models for a range of particle types. He also noted that grid models ignore removal processes in the grid cell into which they are first emitted, so unless the grid size is very small (100 to 1000 times smaller than currently used in regional modeling), they would not be sensitive to removal on the scales (10 to 1000 meters) discussed in this paper (Irwin 2003). Thus, there would be no need to estimate CF, ED and TF for use with grid models if very small grids were used. However, use of grid models in this way would be well beyond current computer capabilities.

[Dong, Yayi, R. Hardy and M. McGown (2003). "Why Road Dust Concentrations are Overestimated in Eulerian Grid Models", in Appendix K, Northern Ada County (Idaho) PM10 Maintenance Plan. Idaho Department of Environmental Quality, June 2003.]

[Irwin, John (2003). U.S. EPA, Research Triangle Park, NC. Personal Communication to T.G. Pace, June 16, 2003]

Recommendations for Fugitive Dust Emissions Estimation and Air Quality Modeling

Use of the TF method in grid modeling is left to the user's discretion. Based on the discussion above, it seems prudent to apply the TF concept when using grid models to compensate for their limitations in resolving near source removal when large grid sizes are used. EPA intends to use it in future regional modeling applications and efforts to incorporate it into the SMOKE emissions processor have begun. However, it is recommended that for Gaussian model applications, one should utilize Gaussian model input parameters whenever possible to account for near source dust removal.

Many refinements have been made to the dust emissions estimation and air quality modeling methodologies over the years; however, significant issues remain:

1) Improvements are needed to the emission estimation algorithms, such as correcting (reducing) the emissions for lower vehicle speeds;

2) Improvements are needed to activity data such as vehicle miles traveled (VMT), silt content and soil moisture on unpaved roads, surface loading on paved roads and soil conditions during agricultural tilling operations and windblown dust events;

3) Improve both the physical and empirical understanding of the near-source enhanced deposition (ED) processes (e.g., thermal and electrostatic forces, agglomeration);
4) Improve the capture fraction (CF) to account for the types and leafiness of vegetation;
5) Improve the concept of the capture (CF) and enhanced deposition (ED) fractions to account for the effect of atmospheric stability.
6) Incorporate and test the methodology to include removal due to CF and ED into regional scale air quality models;
7) More guidance on the specification of specialized input parameters is needed;
8) Continue to improve the removal mechanisms in both grid and Gaussian models.

Conclusions

Our understanding of factors affecting particle removal near ground level fugitive dust sources has improved greatly since the late 1990's. Models are limited in their ability to fully account for near source removal of particles for a variety of physical and practical reasons and this limitation is a major reason for the disparity between modeled and monitored estimates of fugitive dust. The Transportable Fraction concept is consistent with research on windbreaks and has been at least partially quantified by the field work of DRI and MRI. In its current form, the TF concept does provide a useful way to account for this removal process in grid models by applying a variable adjustment across the U.S. This variable adjustment is an improvement upon the national divide-by-four adjustment that has been used for several years. However, this area of research is still emerging and other approaches or assumptions may be useful, especially when considering a specific air shed. Also, it will be prudent to review the TF methodology as new studies are published.

Acknowledgements

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